Technology for an Earth Observing Deployed Lidar Telescope

L.D. Peterson, J.D. Hinkle, J.N. Footdale, S.K. Jeon
University of Colorado
Center for Aerospace Structures
Department of Aerospace Engineering Sciences
Boulder, Colorado 80309-0429

S. Ismail
NASA Langley Research Center
Atmospheric Sciences
MS 401A
Hampton, Virginia 23681

***Abstract*-This paper presents an overview of the Deployable Optics Modeling Experiments (DOME), Advanced Component Technology (ACT) project. The goals of this project are to develop and advance to flight readiness high-precision deployable structures technology to enable space-based lidar measurements. Key technologies include precision deployment, microdynamic stabilization, and modeling of zero gravity stability. These technologies are being verified through subsystem experiments on a single deployed reflector petal derived from a 1997 NASA LaRC lidar receiver concept.**

I. INTRODUCTION

Precision deployable structures for space-based telescopes and instruments will be a key space engineering challenge for the next several decades. A variety of missions envision the use of such structures, whether they be for Earth observation lidar, space based astrophysics, and extraterrestrial planet finding. Whether they operate in IR, visible or UV, all these applications share similar requirements for extremely stable and accurate deployed configurations that maintain their shape to with a fraction of the relevant wavelength of light.[1-3]

The most important engineering goal in these systems will be to achieve the necessary configuration, stability and accuracy for lowest overall system cost. When viewed from a systems perspective, deployment of the instrument structure has the potential to save significant cost. Most precision large space structures are not so much constrained by mass as by volume or dimension of the launch vehicle shroud. Deployment can allow a larger instrument to fit within a smaller, and hence lower cost, launch vehicle. [4]

Deployment, however, introduces perceived risks that must be addressed. Deployment means that the structure has articulated elements or “joints” that impart degrees of freedom and allow motion. Parts of the structure must move through many meters of motion, ending up within very tight tolerances, often less than a few microns of the intended position. Once deployed, the structure must hold its position and remain stable within perhaps higher tolerances under on-orbit loads.[1] Any remaining error is accommodated through active optics, if necessary. Sometimes the structural requirement can be met with simple two-dimensional deployment. Often, a designer would prefer to have the ability to deploy the structure in three-dimensions to increase the structural depth. Deployabled depth can lead to significant increases in overall stability for a given mass, or it can reduce the mass to achive a needed level of stability.[5-7]

In the case of deployed radio frequency (RF) reflectors, the state of the art can deploy structures with perhaps part per per 10,000 stability and precision. [8] In other words, a 10-meter diameter RF antenna might be deployed and stabilized to within a fraction of a millimeter. But when the precision increases to what is needed for optical instruments, the design of the joints requires particular care [9,10]. Phenomena arise due to the optical-scale friction and anelasticity in the mechanisms and materials. This has been called “microdynamics” in the literature [11].

So a natural trade arises between the complexity of the structural deployment and the use of active optics to correct for remaining structural deficiencies. In a complex trade like this, it is important to understand what defines the limits of each, and then work to improve that limit as needed.

Beginning in the middle 1990’s, NASA Langley Research Center (LaRC) and the University of Colorado (CU) initiated a cooperative basic research program to investigate this question. In the late 1990’s, the results of this effort were applied to a deployable lidar telescope reciever. This program developed both design principles and hardware for optically stable mechanisms such as hinges and latches. It resulted in a deployable telescope concept developed by Composite Optics, Inc. [12]. The deployed telescope concept is shown in Figure 1. The overall diameter of this particular telescope is approximately 2.5 m^2. A single petal of this structure was actually built (Figure 2). Details of the mirror and deployed structure construction are in [12], and the results of initial verification tests are in [13].

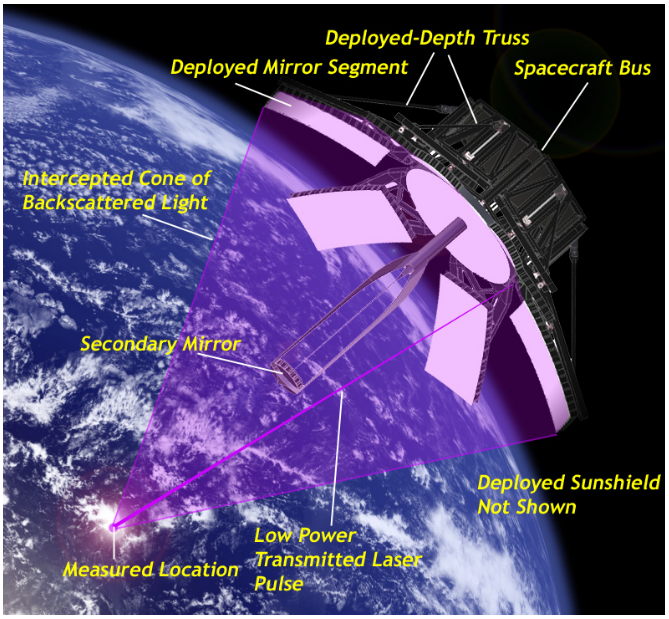

Figure 1. Concept for a space-based lidar telescope receiver.

Althought intended for a Pegasus launch vehicle), this telescope was in fact a "large space structure" in the sense that its deployed size is larger than its launch vehicle shroud allows. Its deployment is somewhat more complex than early concepts for the James Webb Space Telescope (JWST) [3]. The key advantages of this concept were low hysteresis mechanisms and a deployed depth mirror support structure. These two factors together meant that this concept can be, for a given mass, perhaps 50 times the relative overall stability and precision of JWST deployment approach. Whether this was to be realized remained an open question.

In 2002, CU and LaRC proposed a program for the Advanced Component Technology (ACT) program within the NASA Earth Science Technology Office (ESTO). This project is known as DOME for Deployable Optics Modeling Experiments. The overall goal of DOME is to perform the experimental verification necessary to advance this precision deployment technology to flight readiness. It also aims to develop new modeling and verification technologies that support the development of very large telescopes, well over 10 meters in diameter. For such diameters, a requirement to test the performance of the telescope before flight might lead to very high mass penalties. [14]

DOME nears the end of its program. The purpose of this paper describes the current status of the DOME experiment and modeling efforts. The remainder of the paper describes each program element individually.

Figure 2. Single-petal test article extracted from the six-petal concept. DOME is performing experiments on this test article to validate models if its precision and stability at submicron levels of motion.

II. DOME Program Elements

DOME consists of three primary technical elements and objectives described in the next 3 subsections.

A. Precision Latching

Prior testing of the single-petal test article discovered significant deployment precision error due to the design of the latch preloading mechanism. This was reported in [13]. DOME has sought to develop a new latch that replaces the original latch. The new latch is expected to have micron level repeatability, high stiffness and low hysteresis. The design principles reported in [9] and [10] form the basis for this design. Previous tests reported in [15] were able to diagnose the latch deficiency as a lack of preload direction control in the latch. Figure 3 shows an exploded rendering of the new latch and a photograph of the latch assembly. Note that the preload in the latch can be changed as an experimental variable.

A key element of the latch design is the use of ball bearings to transmit load and stiffness. This has the important feature of controlling the stress distribution within the latch, so as to make the friction predictable from theoretical models. Future designs can use this approach and reduce the amount of empiricism necessary in precision mechanism design.

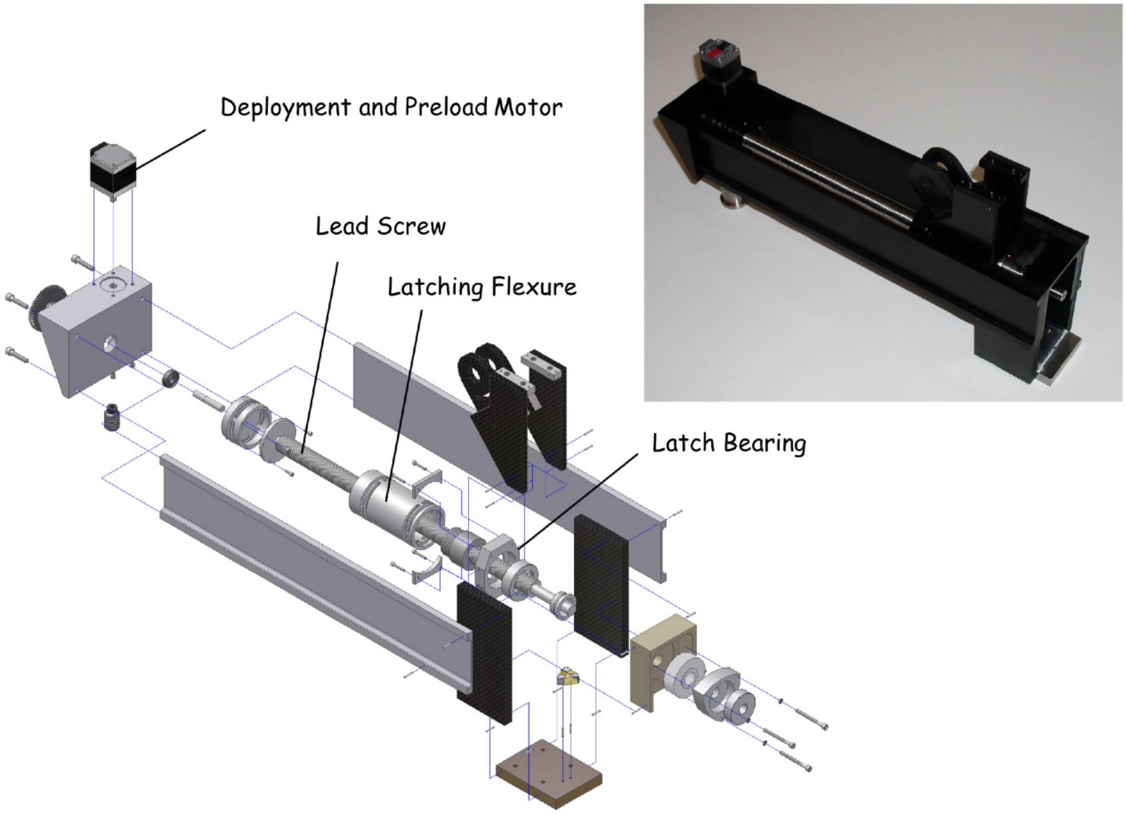

Figure 3. Redesigned DOME Latch.

B. Component Experiments

Component experiments have also been developed to verify the performance of the latch A rendering of the latch test apparatus design is shown in Figure 4.

A unique approach has been developed for actuating this experiment. Because of the nonlinearity in the latch, it is important that the forces that are applied accurately represent the loads exerted when the latch is placed in the structure. But since the unknown latch mechanics determine these loads, they are not well known before hand. We have therefore adopted a “hybrid testing” method. This method simulates the coupling of the rest of the structure to the latch, by simulating the structure with a feedback control law. This was reported in [16]. Figure 5 shows a rendering of the actuation hexapods. Each hexapod controls six degrees of freedom (DOF) of forces and moments at a given boundary location. Two hexapods are used in the latch experiment, one on either side of the latch.

C. Single-Petal Experiment

The single-petal experiment is intended to validate the mechanical performance of the single-petal test article with the new latch design. A rendering of the single-petal experiment is shown in Figure 6, and a photograph of the experiment is shown in Figure 7.

The single-petal experiments will control and vary as appropriate:

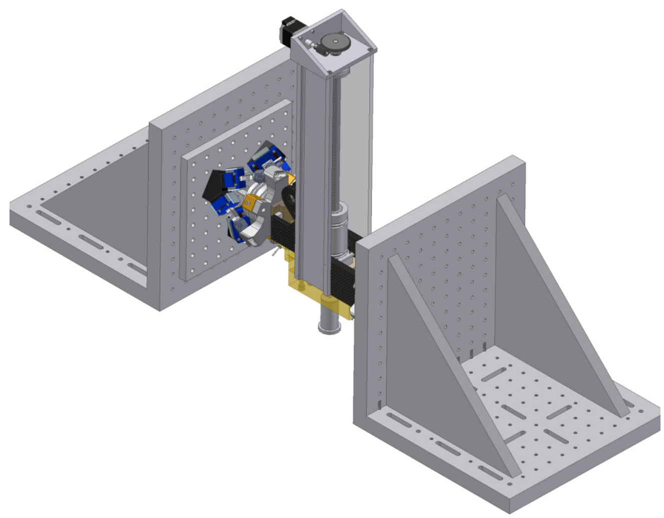

Figure 4. Rendering of the latch test apparatus.
Forces simulating the compliance at the boundaries of the component are imparted by two 6 DOF active boundary condition hexapods
(only one is visible).

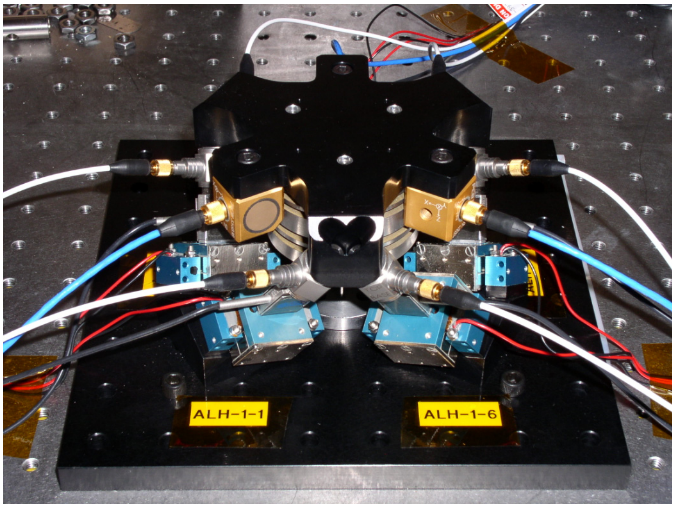

Figure 5. Photograph of one of the active boundary condition hexapods. These provide 6 DOF of actuation at boundary points for both the component and the single-petal experiments.

(a) the thermal environment

(b) the gravity orientation

(c) the deployment state history

(d) the elastomechanical boundary conditions, and

(e) the preload in the latch mechanism.

Two sets of measurements have been designed:

- Performance-related measurements: Structural DOF that determine the optically relevant shape and position of the mirror front surface relative to the interface between the single-petal test article and its intended attachment to the remainder of the telescope.

- Modeling-related measurements: Structural DOF that provide sufficient information to determine likely sources of error within a comparative model of the experiment.

These DOF are measured with respect to a highly stable metrology frame that rests behind the test article, as indicated in the rendering. The metrology frame is designed to have both high thermal and vibration stability. Thermal deviations less than 70 nanometers in any axis at all measurement locations are expected.

The measurement sensors include high precision accelerometers and eddy current sensors. In addition, the experiment uses a special, high-resolution videometry system with 10-20 nanometer accuracy. This videometry system provides a second witness to the static stability and deployment repeatability measured by the eddy current sensors.

As in the component tests, the single-petal tests also incorporate active boundary condition hexapods. These are attached at three locations, providing 18 DOF of boundary

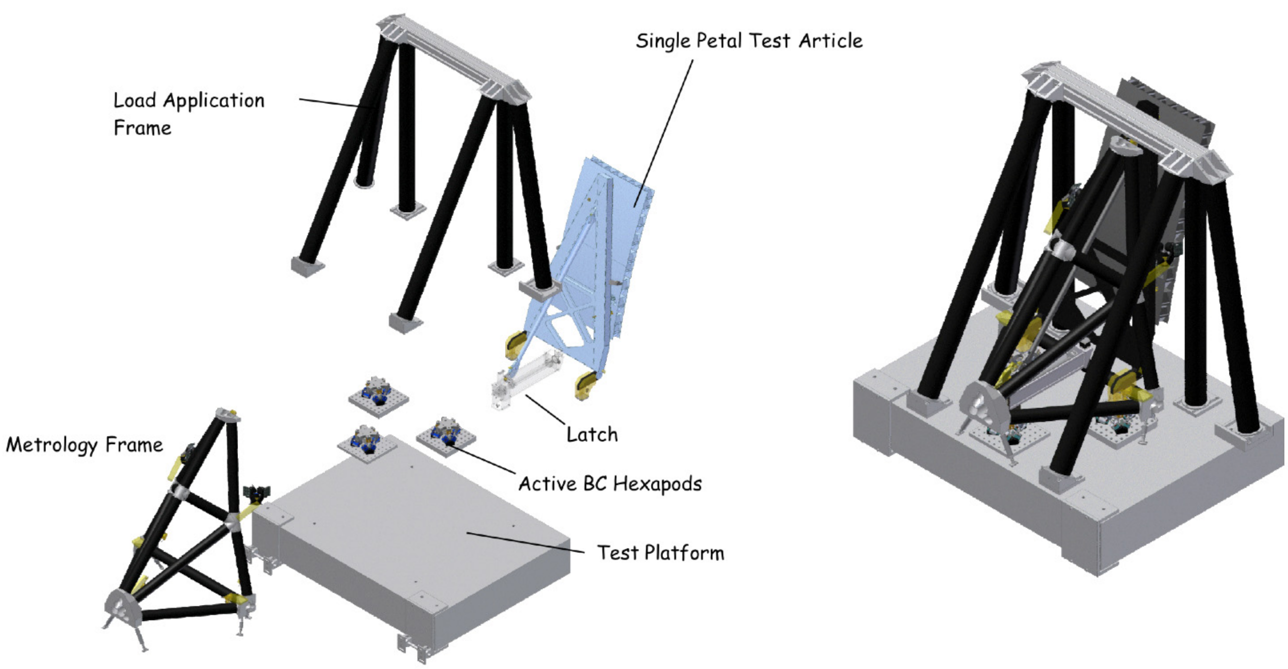

Figure 6. Rendering of the single-petal experiment apparatus.

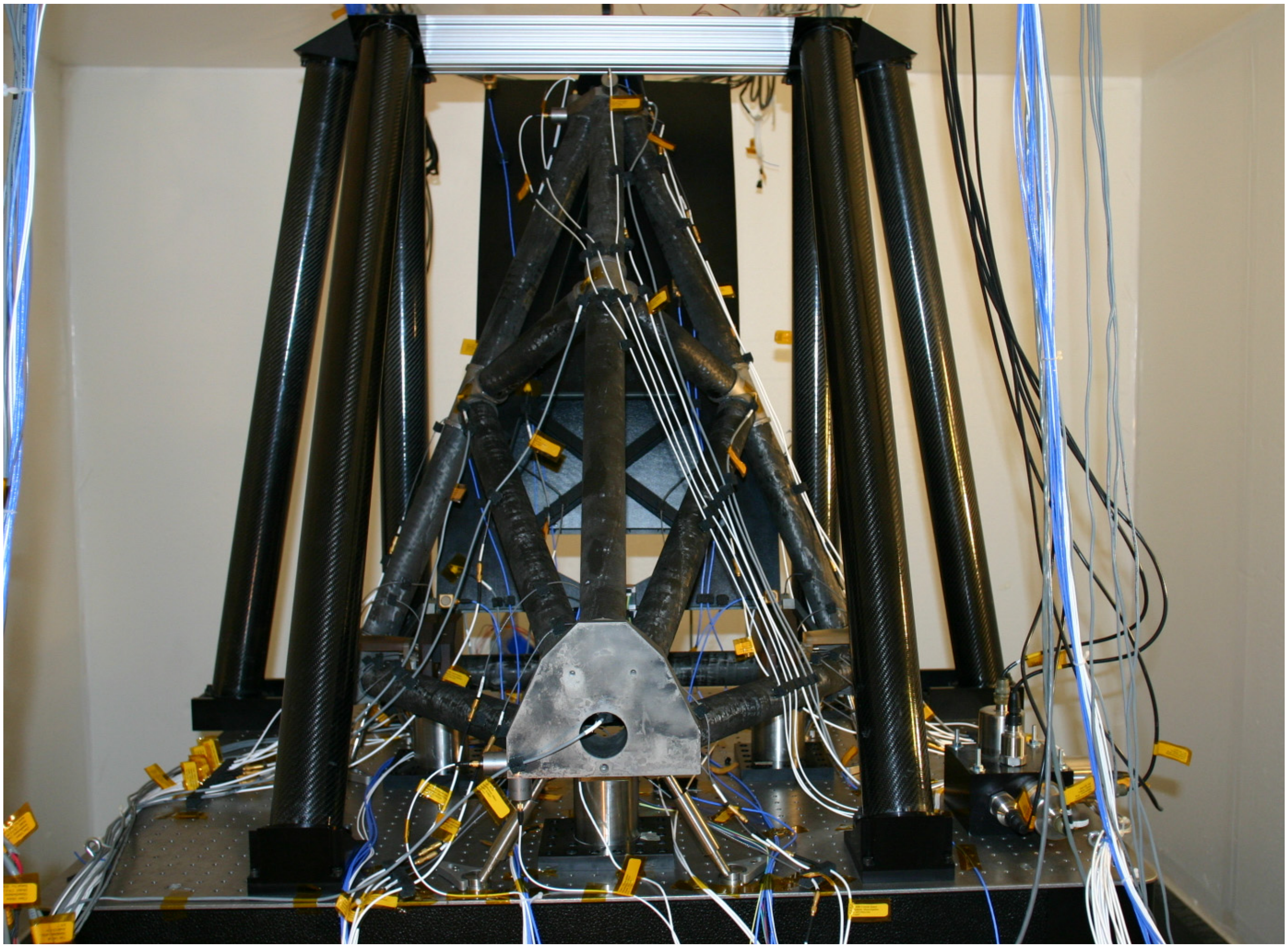

Figure 7. Photograph of single-petal test apparatus.

condition control.

C. Models

The DOME has also developed the following theoretical models:

- Latch Model: Predict the observations of the latch experiments
- Single-Petal Model: Predicts the observations of the single-petal experiment.
- Flight System Model: Predict the performance of the full six-petal deployable telescope in zero gravity.

Figure 8 shows the finite element model used for the single-petal model. It contains approximately 500,000 degrees of freedom, with special detail added to model the stress distribution within the hinge and latch mechanisms. In particular, a new nonlinear finite element has been developed for the ball bearings in the hinges and the latch. These elements model in full six degrees of freedom the nonlinear stiffness and friction effects in the ball bearing contacts.

V. Conclusions

This paper has reviewed the objectives and design of the Deployable Optics Modeling Experiments ACT project. The overall objective of this project is to advance key technology for the deployment of space-based lidar receivers from 2 to 10 meters in diameter. The project has developed a series of component and subsystem experiments, correlated with models, that will lead to a prediction of on-orbit performance of the telescope.

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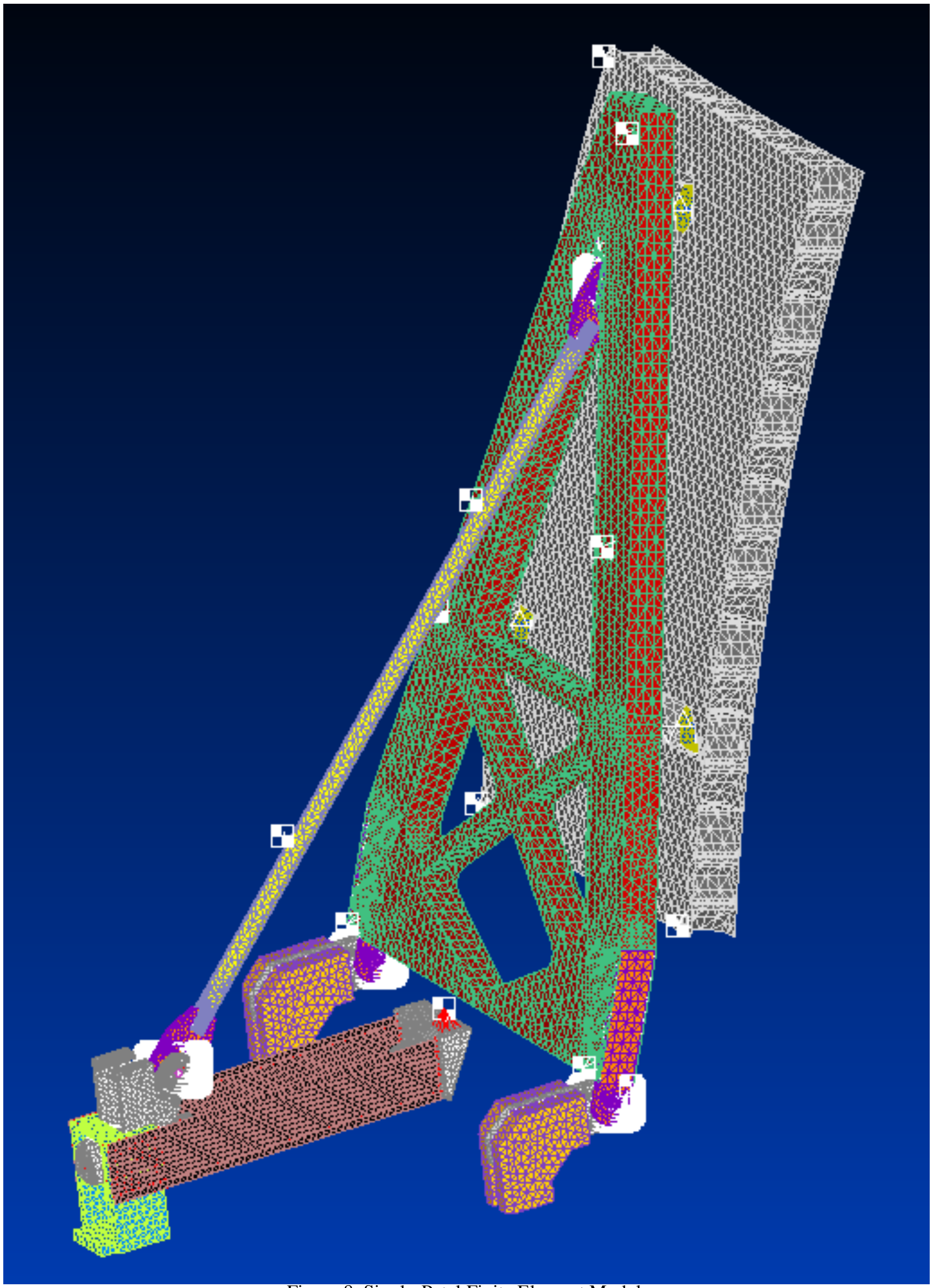

Figure 8. Single-Petal Finite Element Model.

under contract NAS1-03009, with W.C. Edwards as the technical monitor.

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